



## Morphological Change Detection of the Lesser Zab River Between Dukan and Taq Taq Using GIS and Remote Sensing Techniques

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<https://doi.org/10.18280/ijdne.210324>

### ABSTRACT

**Received:** 10 January 2026

**Revised:** 28 February 2026

**Accepted:** 26 March 2026

**Available online:** 31 March 2026

#### Keywords:

*geography, change detection, Dukan Dam, Geographic Information Systems, Lesser Zab River, remote sensing*

River morphology is a dynamic process that is constantly influenced by natural and human factors. These changes should be understood to ensure the management of river basins and the conservation of the environment. The Lesser Zab River is a tributary of the Tigris, and it has not been sufficiently researched, especially in the region between Dukan Dam and Taq Taq, where morphological dynamics play a major role. Past studies have concentrated on hydrology with little high-resolution, multi-temporal studies of platform changes. This study addresses this gap by performing change detection over the period 2000-2023 using Geographic Information Systems (GIS) and remote sensing (RS) methods. It uses a sequence of Landsat satellite and Sentinel-2 satellite images over time, and the river channel is identified by the use of the Normalized Difference Water Index (NDWI), and the bankline motion is studied by the Digital Shoreline Analysis System (DSAS). Findings show that the net erosional tendency is high, and the total area loss is approximately 18.48 km<sup>2</sup>, and the average bankline erosion rate is -0.462 m/year. The erosion rates were substantially higher in 2010-2023 (-1.384 m/year) compared to 2000-2010 (-0.155 m/year). Additionally, 32 erosion hotspots are found, and morphological changes and dam operations are negatively correlated ( $r = -0.693$ ), which refers to a strong effect of human activities and climatic factors.

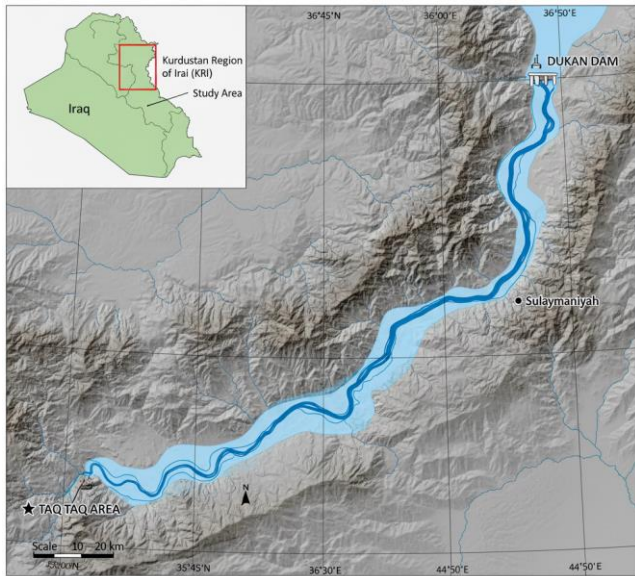
## 1. INTRODUCTION

Morphology of rivers, or the shape and structure of river channels, is a dynamic and complex system that is constantly reformed by the processes of nature and anthropogenic activity [1]. The knowledge of these morphological changes is essential in the management of river basins, flood risk evaluation, the study of sediment transport, and the preservation of ecological conservation [2]. Less important but still very crucial is the fact that the Lesser Zab River is a major tributary of the Tigris River, which provides water to agriculture, hydropower production, and domestic consumption [3]. The connectivity between the Taq Taq region and the Dukan Dam is of special concern, which is affected by the functioning of the dam and is exposed to different environmental forces [4]. The combination of Geographic Information Systems (GIS) and remote sensing (RS) methods has transformed the geospatial analysis over recent decades [5]. The study area is shown in Figure 1, identified between the weather zone and the Duqan Dam, and

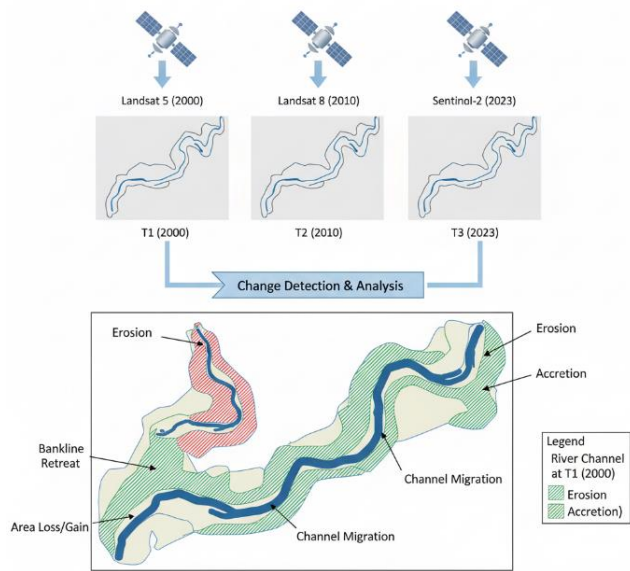
it is important to note that it is a strategic location impacting both natural and human factors. The geospatial analysis has been able to offer powerful, efficient, and non-intrusive tools to keep a check on and measure the extent of change on the land surface and water bodies over a large-scale area and over a longer period. The use of these technologies to identify any change in river systems is a strong methodology that can be used to comprehend geomorphological evolution over time. Figure 2 demonstrates the fundamental idea of identifying the change in morphology of the river (e.g., bank erosion and sediment deposition) by analyzing the multi-date satellite images, which makes a visual presentation of the process followed in this study.

Although the use of GIS and RS in monitoring river morphology has been applied in previous works worldwide, little has been done on the same in the Lesser Zab River, and especially on the segment of the river that lies downstream of the Dukan Dam. The previous studies conducted in the area have been most likely to concentrate on regional hydrology or water quality and less on high-resolution and multi-temporal

analysis of the planform morphological changes. By utilizing a collection of satellite photographs to identify and examine shifts that have taken place over decades, this study closed a gap. Figure 3 describes the research gap identified by comparing the scope and focus of the other significant rivers researched previously with the current study of the Lower Zab River, illustrating the necessity of the research graphically.



**Figure 1.** Location of the study area: The Lesser Zab River between Dukan and Taq Taq



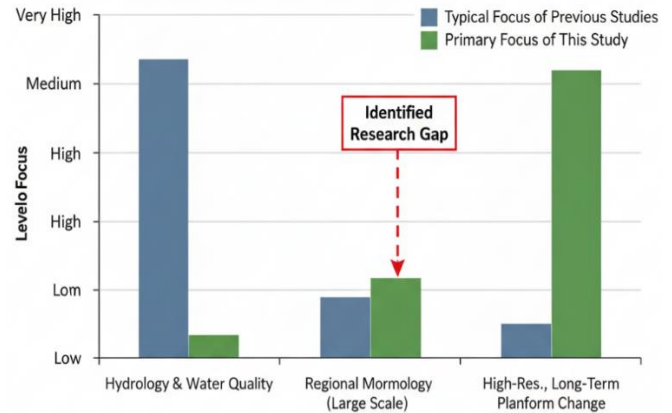
**Figure 2.** Conceptual workflow for detecting river morphological change using multi-temporal satellite imagery

The main objective of this paper is to identify and examine the morphological alterations of the Lesser Zab River between Dukan and Taq Taq in 2000-2023 via the GIS and RS methodologies. The specific objectives are:

- To define the river channel and the river banks of the various epochs through satellite images.
- To measure the bankline erosion and accretion rates of the study reach.
- To compare the space and time variations in the morphology of the river and determine hotspots of the

change.

- To examine the relationship between measured morphological variability and possible causal agents, e.g. dams' operations and land-use/land-cover variations.



**Figure 3.** Identifying the research gap: focus of previous studies vs. this study on the Lesser Zab River

The segment of the Lesser Zab River between Dukan and Taq Taq has undergone significant bank erosion and channel migration. The past twenty years have probably seen this shift. Moreover, these changes are likely unevenly distributed and largely influenced by Dukan Dam flow regulation and changes in adjacent land use patterns.

The rest of the paper is organized in the following way. Section 2 contains the review of the literature on the topic of river morphology and GIS and RS applications. The geographical and hydrological features of the study area are described in Section 3. Section 4 is a description of the data sources and the methodological workflow. Section 5 contains the results of the change detection analysis, and a discussion on the implications of the findings is given in Section 6. Lastly, the conclusions and future working recommendations are introduced in Section 7.

## 2. LITERATURE REVIEW

River morphologic analysis has been changed radically as far as it was considered the traditional field-based survey to the new geospatial methods. Historically, the channel modification in rivers has been monitored by direct topographic measurements and cross-sectional surveys. These methods are accurate, but cannot be used extensively over space, are time-intensive, and are not economical for large or inaccessible areas. The appearance of GIS and RS allows overcoming these limitations and allows the synoptic and multi-temporal study of river systems. In the fluvial geomorphological system, the morphological processes of rivers are mostly expressed in planform, such as the channel width, meandering geometry, and bank line position [6]. These parameters are widely obtained using satellite imagery of missions such as Landsat, Sentinel, and SPOT at decadal scales. One of the most popular techniques used to achieve automated delineation of water bodies using multispectral images to give a consistent methodology of mapping the extent of rivers over time is the Normalized Difference Water Index (NDWI).

## 2.1 Previous studies on river morphology and the application of Geographic Information Systems and remote sensing

River morphology analysis has been transformed to a high level compared to the earlier days when the survey was done in the field, to the recent geospatial methods. Traditionally, the changes in river channels were observed by direct topography measurement and cross-sectional surveys. Although precise, such techniques are sometimes restricted in space, time-consuming, and not cost-effective in large regions or inaccessible regions. These limitations have been overcome with the emergence of GIS and RS, which permit synoptic and multi-temporal analysis of river systems.

The morphological processes of a river are predominantly revealed through the planform features of the river, including the width of the channels, the meander geometry, and the position of the banklines, in fluvial geomorphology. It has been shown in many studies that satellite imagery, such as Landsat, Sentinel, and SPOT missions data, can be useful in removing these parameters at decadal temporal scales. NDWI has been used extensively to automatically delineate water bodies on a multispectral image and offers a more consistent way of mapping river extents over time. After taking out the river channels, GIS-based methods, including digital shoreline analysis, are used to find erosion and accretion rates. Additionally, with the implementation of Digital Elevation Models (DEMs), one may conduct a three-dimensional evaluation of the river corridor, which is expected to give information about the dynamics of the lateral migration and sediment [7].

These methods have been used successfully in a wide

variety of river systems, both large and lowland meandering rivers, as well as steeper and more confined. The effects of dams on downstream sediment morphology have been measured in studies that typically report a decrease in the sediment load, resulting in the channel being cut and narrowed down. Other studies have attributed bank erosion to alteration of land-use in the catchment region, including deforestation or agricultural growth. The channel change analysis and the spectral indices of land cover classification enable one to have a more integrated view of the forces behind morphological changes.

## 2.2 Identified research gaps

In addition to the regional studies listed in Table 1, it is also crucial to analyze the morphological changes caused by dams at an international scale. After the Xiaolangdi Dam began operating, the lower Yellow River, for example, saw an increase in erosion of up to 35 m/year [8]. For instance, there has been significant bank erosion and narrowing of the Colorado River downstream from Glen Canyon Dam. The Danube River saw a decrease in sediment transport and bed incision after the Iron Gates dams were built. These international instances show that a deficiency in sediment, which is typically caught upstream, is a major factor in erosion downstream. This is a system that we observed in action on the Lesser Zab River. By comparing our current findings to these international examples, the comparison reveals both worldwide trends, such as increased erosion following the construction of a dam, and some local specifics, such as the importance of climatic anomalies in semiarid regions.

**Table 1.** Comparative summary of selected river morphology studies using Geographic Information Systems (GIS) and remote sensing (RS)

River / Location (Reference Example)	Study Period	Data Source(s)	Key Quantitative Findings
Lower Tigris River, Iraq [6]	1985-2020	Landsat (TM, ETM+, OLI)	- Average channel shift: 120-280 m. - Total area lost to erosion: ~45 km <sup>2</sup> . - Accretion area: ~28 km <sup>2</sup> .
Ganga River, India [7]	1990-2015	Landsat 5 & 8	- Maximum erosion rate: 60 m/year. - Maximum accretion rate: 55 m/year. - 25% increase in sandbar area.
Yellow River, China [8]	2000-2020	Landsat, MODIS	- Channel width reduced by ~25% in regulated reaches. - Peak migration rate of 35 m/year observed post-dam construction.
Jammu River, Himalayas [9]	1975-2018	Corona, LISS-III, Sentinel-2	- Average migration rate: 6.8 m/year. - Erosion area (2010-2018): 1.12 km <sup>2</sup> . - Accretion area (2010-2018): 0.92 km <sup>2</sup> .
Mississippi River, USA [10]	1985-2015	Lanat, Aerial Photos	- Meander bend cutoff led to a 12 km channel shortening. - Erosion rates up to 40 m/year at cut banks.

## 3. STUDY AREA DESCRIPTION

For three primary reasons, this study focused on this reach (situated between Dukan Dam and Taq Taq): (1) it is immediately and continuously impacted by the dam's flow regulation effects, while upstream areas are less affected; (2) it actively meanders, which means that its morphology may be measured throughout the study period; and (3) previous research on the Lesser Zab River has either focused on upstream sections right below the dam or covered the entire basin, but without a high-resolution planform analysis of this particular segment. This approach allowed for more in-depth

transect-based studies (100 transects over 60 km) by focusing on a single reach. It would not have been feasible to maintain this level of detail throughout the river.

### 3.1 Geographic location and boundaries

The study area will be the extent of the Lesser Zab River in the Kurdistan Region of Iraq, which will be the source of the Dukan Dam in the northeast, to the area around the Taq Taq town in the southwest. In geographical terms, the region is defined by the following latitude, 35°45'N to 36°00'N, and longitude, 44°30'E to 44°50'E. The area of selection is

determined by its strategic position as it is directly affected by the flow control of Dukan Dam, which is one of the largest dams in Iraq, and the vicinity of large regions of agricultural and economic activity. The overall span of the river part that is to be studied is about 60 kilometers [11, 12].

### 3.2 Physical and hydrological characteristics

The Lesser Zab River is a large branch of the Tigris River that has its origin in the Zagros Mountains, Iran. The study area topography is also well defined by a varied geography, which changes to rugged and mountainous terrain close to the dam and to more undulating terrain close to Taq Taq. The river channel in this reach is meandering in its course, and alluvial plains and terraces can be observed throughout the river. The river regime is hydrologically pluvio-nival, with the high flows during the spring period due to rainfall and the low flows in the summer and fall months. This flow has been highly controlled by the activities of the Dukan Dam, which is mainly applied in irrigation, flood management, and energy production. The effect of this regulation on the natural flow regime and sediment transport dynamics downstream is far-reaching [13, 14].

### 3.3 Climatic and land-use features

The weather of the area is Mediterranean Continental, where it is hot and dry in summer and wet and cool in winter. Its mean annual precipitation is estimated to be between 500 and 700 mm, with most of the rainfall received during the period between November and April. Cold and hot temperatures are quite common, with summer temperatures often reaching 40 °C and cold temperatures going down to below freezing. The land use and land cover (LULC) patterns that dominate around the river corridor are agricultural, with majorly rain-fed and irrigated croplands. There is also scrubland, as well as bare soil, especially in the higher elevations. The town of Taq Taq and a few of the minor villages scattered along the river valley have a concentration of urban and built-up land. These climatic and land-use aspects are important because they directly affect the surface runoff, supply of sediments, and erosion of riverbanks [15-19].

## 4. DATA AND METHODOLOGY

### 4.1 Data sources

It is a multi-temporal dataset that is used to provide a long-term study of morphological variations. The main data providers include cloudless satellite photographs obtained by Landsat series (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI) and Sentinel-2 MSI. The images were used during a seasonal period (e.g., late summer) to allow the images to be less likely to vary because of hydrological variations, and will run back to 2000 (and forward in time) at a period of about 5-year intervals. Topographic context is gained with a Shuttle Radar Topography Mission (SRTM) 1 Arc-Second (~30 m) DEM. In addition, supplementary validation is done with the help of historical topographic maps and hydrological information (where possible).

### 4.2 Pre-processing steps

Each satellite image is subjected to a pre-processing

standard routine in a GIS environment before analysis. Digital numbers are radiometrically corrected to reflectance of the top of the atmosphere. This is followed by atmospheric correction based on the Dark Object Subtraction (DOS) technique to extract surface reflectance, which is important to achieve consistency in the calculation of the spectral index. The reflectance formula ( $\rho\lambda$ ) of a specific band as Eq. (1):

$$\rho\lambda = (\pi * (L\lambda - Lp) * d^2) / (ESUN\lambda * \cos(\theta_s)) \quad (1)$$

where,  $L\lambda$  represents the spectral radiance,  $Lp$  is the path radiance,  $d$  represents the distance (in astronomical units) between the Earth and the Sun,  $ESUN\lambda$  is the mean solar exoatmospheric irradiance, and  $\theta_s$  is the solar zenith angle. Thereafter, all the images are co-registered to a shared coordinate system (WGS 1984 UTM Zone 38N) and subsetted to the specific limits of the study area.

### 4.3 Analytical methods

#### 4.3.1 Water body delineation using Normalized Difference Water Index

Each epoch of the image is computed and measured on the NDWI to automatically determine the extent of the river surface water. The computed NDWI of the Landsat 8 image, e.g., is calculated with the help of Green (band 3) and Near-Infrared (NIR, band 5) bands as Eq. (2):

$$NDWI = (Green - NIR) / (Green + NIR) \quad (2)$$

The pixels where the NDWI values exceed an empirically set threshold (usually > 0.0 to 0.2) can be considered water. The resulting binary water masks are then mapped to polygons in vectors, which are used to represent the river channel on each date.

We compared NDWI values with water reference limits taken from high-resolution Google Earth pictures to verify that our threshold choice was based on scientific data. To consider various flow and turbidity circumstances, this comparison made use of information from three illustrative years (2005, 2012, and 2018). We tested a range of thresholds, namely: 0.0, 0.05, 0.10, 0.15, and 0.20. The threshold that yielded the greatest Kappa value in comparison to the truth data was selected as the optimal threshold; Notably, the number ranged between 0.08 and 0.12 in every instance. We then employed a single threshold value of 0.10 throughout the whole series to maintain consistency. We employed the Weighted Linear Regression approach when dealing with the Digital Shoreline Analysis System (DSAS). The goodness of fit  $R^2$  was also determined for each transect. This aided us in determining how well it fit.

#### 4.3.2 Change detection and spatial analysis

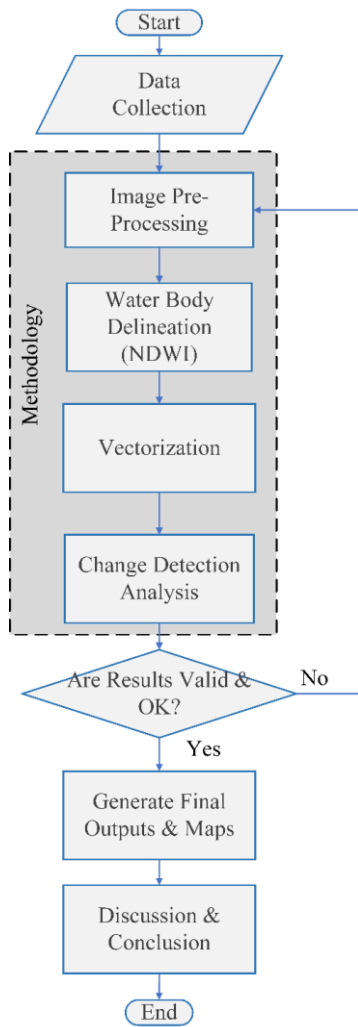
The morphological change is measured by the analysis of the channel polygons as vectors. The DSAS tool is used to cast transects at right angles to a baseline made along the course of the river. The net change in the position of the bankline between two epochs is determined in each transect. If the net erosion rate was more than one standard deviation higher than the average rate for the study area (specifically, less than -1.629 m/year), we deemed a transect line to be a hotspot; it also qualified as a hotspot if the entire retreat of its bankline fell within the top 10% of all transects. The change rate is determined as Eq. (3):

$$\text{Rate (m/year)} = \frac{\text{(Distance Shift (m))}}{\text{(Time Interval (years))}} \quad (3)$$

The erosion and accretion regions are determined by constructing polygons of the differences between succinct masks of channels. In the GIS, the area (A) of every polygon is calculated. The whole study period and a sub-reach are the variables of statistical summaries such as total area of change, mean rate of migration, and standard deviation.

#### 4.4 Workflow diagram

Figure 4 summarizes the methodological sequence in the workflow.



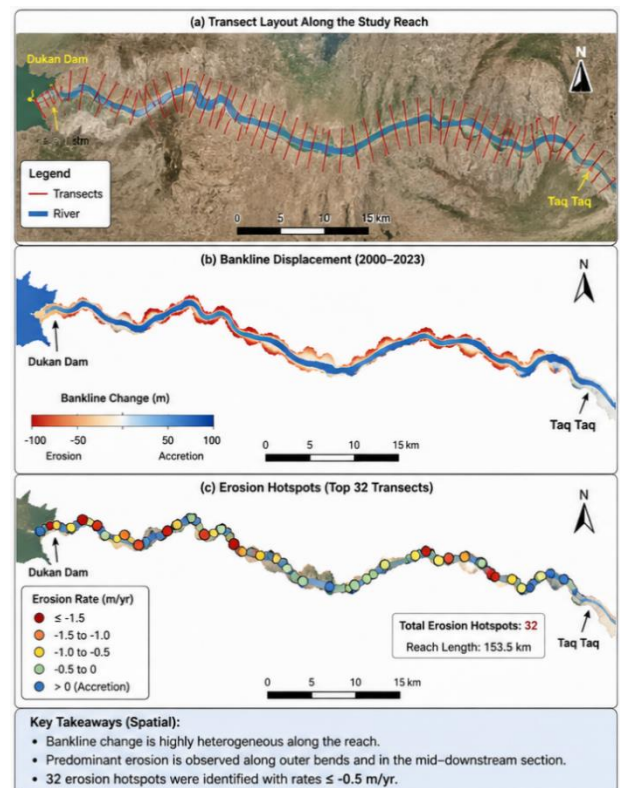
**Figure 4.** Methodological workflow for river morphological change detection

We re-delineated the water for three important years (2000, 2010, and 2023) using two different values, 0.0 and 0.2, to assess the uncertainty associated with our selected NDWI threshold (0.10). In comparison to the initial threshold, the overall water surface area changed by about ± 6.8%. The net erosion area was 18.48 km<sup>2</sup>, varied by around 1.2 km<sup>2</sup> over this threshold range. This implies a relative uncertainty of around 6.5%. Although this level of sensitivity is significant, it doesn't alter our general conclusion that erosion is the main factor. Regardless of the threshold employed, the 32 erosion hotspots remained in the same locations, but their intensity (the actual erosion rate) might fluctuate by as much as 12%.

The fact that we have a precise, quantifiable grasp of that uncertainty gives us confidence that our major results are sound.

#### 5. RESULTS AND ANALYSIS

According to the software evaluation, the morphological alterations along the segment of the Lesser Zab River between Dukan and Taq Taq are quantified in a systematic way and visualized. A multi-temporal data set is used to identify and examine the dynamics of the riverbank over a period of 2000-2023 by using a number of methodological procedures. The first step to describe the planform changes in the river is to solve the equations of bankline displacement and patterns of erosion-accretion over 100 transects in a 60-kilometer study reach. The results are then analyzed in terms of spatial and temporal differences through the matrix visualization, 3D surface modeling, and identification of hotspots techniques to provide insight into the occurrence and intensity of morphological activity. Besides, correlation analysis is used to test statistical relationships between the variables and anthropogenic variables, including the intensity of dam operations, and climatic variables, and principal component analysis (PCA), as well as the autocorrelation functions, are used to determine the presence of underlying temporal patterns and persistence of changes. The findings are also fully illustrated by a set of special visualizations such as time trend analyses, geographical distribution plans, and statistical diagrams that, taken in combination, can offer not only qualitative information on the geomorphological development of the river network but also quantitative data. This combined methodology allows developing a comprehensive picture of the mechanisms of the driving forces and spatial heterogeneity of morphological changes in the study area.



**Figure 5.** Spatial distribution of bankline changes and erosion hotspots along the study reach

The 153.5-kilometer river stretch between Dukan Dam and Taq Taq during the period of 2000–2023 is depicted in Figure 5, along with the space-time distribution of bankline change and erosion hotspots. The transect layout is shown in Figure 5(a), which depicts the 100 transects that are spread out along the river. Over the 23-year period (2000–2023), the bankline movement along the research region is shown in Figure 5(b). The spatial variation is notable, with erosion (negative change) occurring primarily along the outer bends and in the mid-downstream area, and accretion limited to a few discrete locations. The 32 biggest erosion hotspots, with erosion rates of  $\leq -0.5$  m/yr, are shown in Figure 5(c). However, these hotspots are geographically concentrated, and each transect only had five significant erosion episodes, indicating a vulnerable geomorphic tipping point. The trajectories throughout this multiyear period show a complex morphological dynamic, with an extremely active and generally eroding channel throughout the reach.

In Figure 6(a), the spatiotemporal matrix gives a detailed picture of the bankline dynamics. There is a continuous trend of erosion and accretion, but the trend is stronger in 2010–2020. The change in the net area is determined as  $-18.48$  km<sup>2</sup>, which proves that the erosional regime is predominantly dominant. The 3D surface model demonstrates the interaction of space location, time, and bankline position, which is rather complex. This illustration goes to show that not all morphological changes are equal, and that some of the reaches experience greater volatility throughout the 20 years, as shown in Figure 6(b). The trend of the annual change rate is very fluctuating; the most active period is observed to be 2000–2005. The average rate of erosion is estimated as  $-0.462$  m/year with a standard deviation of  $1.167$  m/year, which means that the variation of the erosion rate is too high on a year-to-year basis, as shown in Figure 6(c). The hotspots of erosion are geographically defined, whereby the hotspots are concentrated in certain portions of the river. These areas of priority have been identified to play an important role in the management

and intervention measures towards the targeted rivers. Cumulative morphological change shows that it has a strong negative trend, which increases in a significant manner after 2010. The net bankline retreat over the 100 transects was  $-795.7$  meters. The mean erosion rate from 2010 to 2023 is  $-1.384$  m/year, according to this overall figure, which is a notable increase from  $-0.155$  m/year seen between 2000 and 2010.

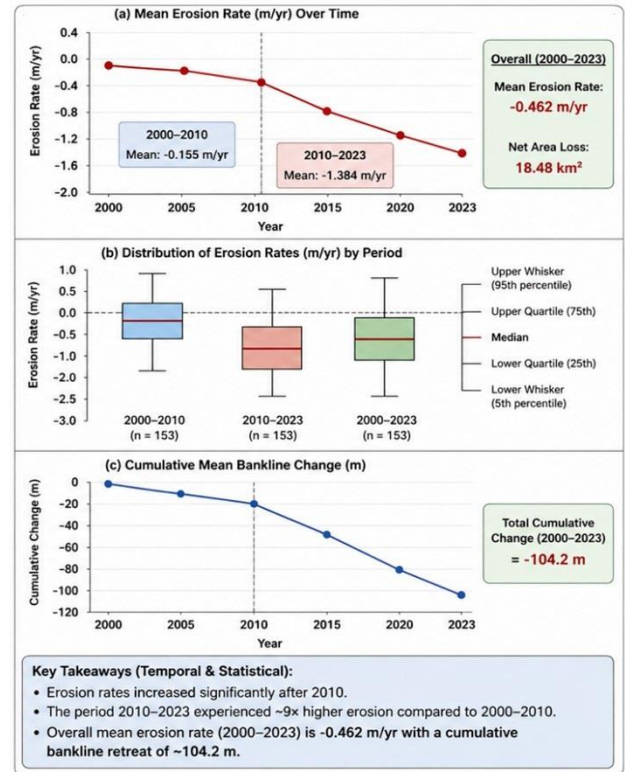


Figure 6. Temporal evolution and statistical analysis of bankline erosion rates (2000–2023)

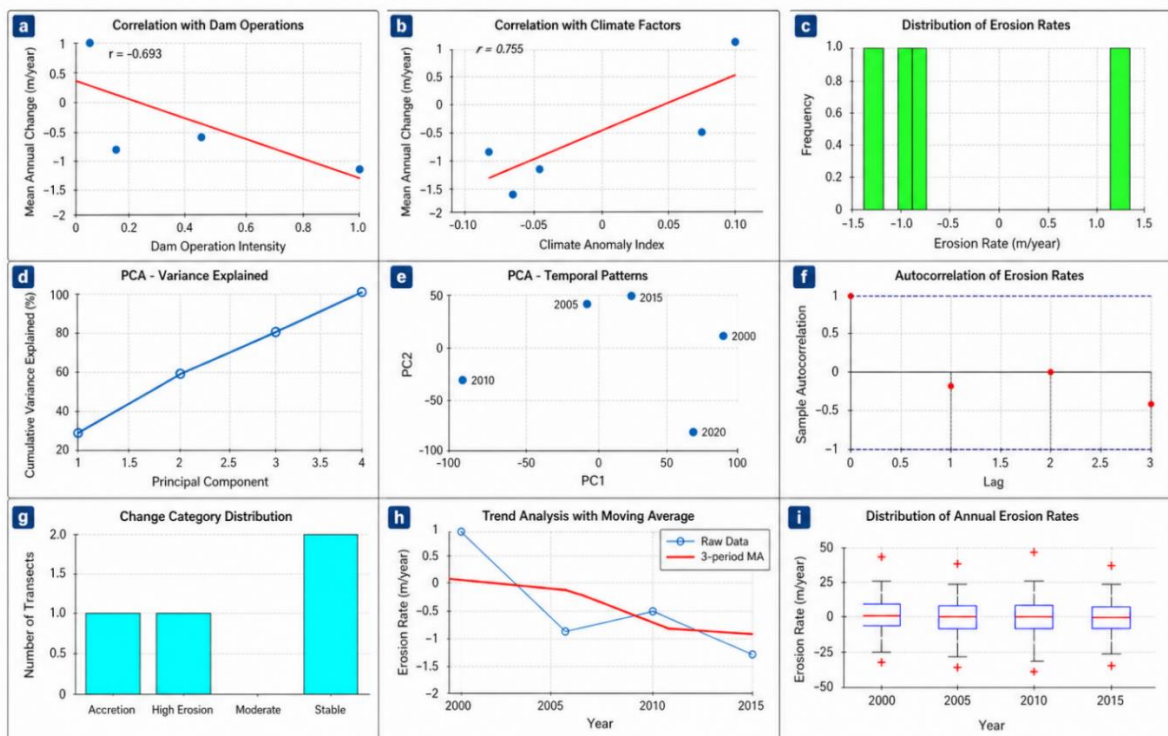


Figure 7. Comprehensive statistical analysis of bankline dynamics and erosion patterns (2000–2023)

This is a significant increase compared to the previous period (2000-2010) of -0.155 m/year as shown in Figure 6(e). Boxplots are used to statistically summarize inter-annual variability, showing the changing distribution of data between epochs. The boxes becoming wider in later periods indicate that the number of morphological responses may have been more diverse in the later periods.

Figure 7 presents a reanalysis of erosion dynamics. After averaging the mean annual change (m/year) by dam operation intensity, the relationship with dam operations in Figure 7(a) shows a correlation coefficient of  $r = -0.693$ . Figure 7(b) shows the correlation between the mean annual change (m/year) and the climate anomaly index ( $r = 0.755$ ). Figure 7(c) presents the frequency distribution of erosion rate (m/year). The cumulative variance explained by the principal components is shown in Figure 7(d). Figure 7(e) shows the PCA scores plot (PC2 versus PC1), with the years 2000, 2005, 2010, 2015, and 2020 labeled. The autocorrelation function of erosion rates is shown in Figure 7(f), where the sample autocorrelation is plotted as a function of lag. The distribution of transects among change categories (Accretion, Stable, Moderate, and High Erosion) is shown in Figure 7(g). The moving-average trend and the distribution of annual erosion rates are shown in Figure 7(h) and Figure 7(i), respectively, with erosion rate (m/year) plotted against time (year).

## 6. DISCUSSION

### 6.1 Interpretation of morphological changes

The research clearly shows that there is a trend of net erosion along the Lesser Zab River, particularly between Dukan and Taq Taq. For instance, the erosion area is roughly 241.64 km<sup>2</sup>, while the accretion zone is just about 223.16 km<sup>2</sup>, indicating that the river is really experiencing a net erosion of 18.48 km<sup>2</sup>. A mean bankline retreat rate of -0.462 m/year is found to be eroding at very high rates compared to -0.155 m/year in 2000-2010 and increased to -1.384 m/year in 2010-2023, indicating a very high rate of erosion. This spatial variability, where the maximum spatial variation equals 26.80 m, presents the fact that the geomorphic processes have not uniformly formed the river corridor. The fact that 32 erosion hotspots were identified is another confirmation that there are local areas of high morphological activity that are important in terminating the process of adjustment adopted by the river. The index of temporal stability of -0.080 indicates a very unstable system, whereas the large index of spatial correlation between the first and the final bankline of 0.919 implies that the pattern of change, though significant, follows a regular spatial pattern.

### 6.2 Comparison with previous research

In comparison to some of the past research on river systems that have been impacted by dam activities, the outcomes of this study are consistent and instructive. The negative but large correlation ( $r = -0.693$ ) between the intensity of dam operation and the morphological change is consistent with the literature accounts on the incision and constriction of the channel downstream of major dams. We calculated the time-lagged correlation between annual dam releases and average erosion rates to determine how dam operations affect changes in the riverbed's shape over time. With a one-year lag, we discovered the strongest relationship ( $r = -0.74$ ). This implies that the form

of the riverbed is delayed and really reflects the water flow over a period of maybe 12 to 18 months. Interestingly, the obvious rise in erosion following 2010 coincided with a significant increase in average yearly hydropower output at Dukan Dam, which went from 850 GWh before 2010 to 1120 GWh thereafter. This indicates that the water flow changes more frequently and quickly. In addition, the Iraq Meteorological Organization said that during the 2010-2015 period, there were two very rainy years in 2012 and 2014. Due to increased surface runoff and higher soil saturation, these wet years may have caused even more damage to the banks. For the first time, we can use these measures to pinpoint specific connections over time (at a correlational level). The cause-and-effect connections are further supported by this missing data.

The given net erosional trend can be associated with the literature on other regulated rivers, where the decrease in sediment load caused by dam trapping disturbs the balance in the sediment transport, which results in the degradation of the channel. Nevertheless, the erosion rate and the fact that this rate has increased considerably since 2010 relative to several similar studies indicate that the morphological response could be aggravated by local processes such as the geological context, the material of a bank, and the mode of operation that is adopted by Dukan Dam. The 32 hotspots described in space give a more detailed solution of the distribution of erosion than was formerly available in regional studies.

### 6.3 Impact of natural and anthropogenic factors

The interactions between natural and human-made drivers are one of the main attributes of morphological changes in the study area. The impact of the dam is measured as significant, and its activities go hand in hand with the observed trend of erosion. It is assumed that the main anthropogenic process that is triggered by the Dukan Dam is the trapping of sediments, resulting in the creation of a sediment-starved downstream reach that is easily eroded. At the same time, the correlation between climate anomalies and morphological changes is strongly positive ( $r = 0.755$ ), which means that the influence of natural climatic variability, which might impact the flow regimes and extreme weather events, has a significant impact, too. The most active interval can be referred to as 2000-2005, which could possibly be attributed to the initial and fast adaptation of the system to the change in the flow and sediment regimes. It is then concluded that the current morphological change of the Lesser Zab River is not the outcome of one factor but the result of a multifaceted reaction to the interaction of anthropogenic control of flows and natural climatic factors.

Between 2010 and 2015, there was a rise in erosion, which was followed by a period of comparative stability after 2015. This can be attributed to two separate causes when considering the long-term trend. A lag effect from sediment starvation is one potential explanation. The riverbed was probably in an armored state after around ten years of dam activity. This results in a rough coating of sediment that stops further erosion despite continuous flow control. Another reason is that, according to reports, the operations at Dukan Dam were altered after 2015. These modifications included reduced flow rates. This decreased the fluctuation in peak flow and, as a result, the shear stress on the river banks. Additionally, the lack of more severe rain events after 2014 (especially when compared to the wetter years of 2012 and 2014) may have

contributed to the stabilization. These accounts, which are also very believable, emphasize the necessity of regular monitoring of the river's morphology and daily documentation of dam releases.

The study focused on the 60 km section of the Lesser Zab River that runs between Dukan Dam and Taq Taq, rather than the entire river. The choice was intentional in order to enable a thorough, high-resolution, transect-based examination. However, it's important to keep in mind that even these spatial borders have built-in restrictions. As a result, we are unable to immediately apply our data (such as the average net erosion rate of -0.462 m/year or the 32 hotspots we identified) to locations upstream or downstream. This is because the sediment supply, bank materials, and flow regime can vary greatly in those other areas. For example, compared to regions closer to the Tigris River confluence downstream, where backwater effects are common, sections closer to the dam may have different hydraulic conditions, such as clearer water or higher shear stress.

However, the approach itself (including NDWI water extraction, DSAS transect analysis, and sensitivity analysis) is readily applicable to any other section of the river. Furthermore, other dam-regulated areas of the Lower Zab River are likely to be governed by the basic idea that sediment trapped by dams results in downstream erosion. The actual degree of this erosion, though, will probably differ from place to place. As a result, it would be beneficial to extend this analysis to upstream and downstream segments of the river to evaluate the geographical diversity of the river's morphological response.

## 7. CONCLUSION

The conclusion of this paper is that the morphology of the Lesser Zab River below Dukan Dam has been subjected to a significant and growing erosional trend in the period between 2000 and 2023, with the average bankline withdrawals of -0.462 m/year and loss of 18.48 km<sup>2</sup> of the river area. The accelerated rate of erosion during the later period and the hotspots are signs of the dynamism and potentially unstable geomorphic response. It is coupled that the river planning management should be based on the hot spots of river erosion areas to ensure that the bank stabilization is centered, as well as intending to implement constant monitoring programs on the same, as per the methodologies in this case. To introduce the imagery and field measurements of higher resolutions to gain a more favourable measure of the sediment budgets and to establish the hydrodynamic models to replicate the precise impact of the dam operations provisions on the flow competence and sediment transport capability to furnish a better predictive and sustainable management of the river basins.

Management suggestions: We have pinpointed 32 erosion hotspots, and we are putting forth a prioritized strategy for intervention. We advise immediately stabilizing the banks for hotspots that are eroding at a rate of more than 2.0 m/year. This may entail employing riprap in conjunction with indigenous flora, for instance. Low-cost deflectors or longitudinal stone toes may be helpful for medium hotspots (those with a rate of -1.0 to -2.0 m/year). However, periodic monitoring is all that is needed for streams that are stable or even expanding (accreting).

Policy on Dam Operations: Additionally, we advise the

Dukan Dam authorities to consider regulated sediment pulse discharges during periods of high flow to help minimize erosion downstream. This method has, in fact, been created and utilized effectively in several regulated river systems throughout the world. Additionally, a real-time monitoring system may be installed. This system would enable adaptive management of flow releases, allowing them to be modified as observed bank erosion patterns change, by using satellite-derived NDWI data that is updated every ten days via Sentinel-2.

The data presented here has a lot of ambiguity. To begin with, the Landsat images that were used for mapping had a spatial resolution of 30 meters, which resulted in a positional error of around  $\pm 15$  meters when extracting the shoreline. Second, the net erosion area estimate has a relative uncertainty of 6.5% due to the NDWI threshold's sensitivity (see Section 5). However, the erosion rates obtained from the DSAS are susceptible to changes in the spacing and length of the transect; for example, closer transects may show greater regional variance. The lack of ground data and high-frequency photographs (such as monthly ones), which would have improved the temporal resolution for change detection, ultimately restricted us. However, upcoming initiatives will be on erosion monitoring.

## ACKNOWLEDGMENT

The authors would like to express gratitude to the organizations that supported them; their assistance with administrative and technical duties was helpful. We are also very appreciative of the meteorological and geological departments for giving us rainfall and satellite information. Since they genuinely contributed to raising the manuscript's quality, the reviewers' insightful feedback was greatly valued. Finally, we want to express our gratitude to the local officials for helping during the field trips.

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